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Porosity Development Within Lobes to Downslope Ramp Deposits on a Prograding Carbonate Shelf of the Kinderhookian to Osagean Series in Northwest Arkansas

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by

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Lehigh University
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Abstract

Carbonate bodies with lobate geometries form a substantial part of the Osagean (early Mississippian) section in northwest Arkansas. The purpose of this study is to isolate and describe a single lobe from three-dimensional exposures in quarry walls to provide criteria by which lobe and lobe porosity can be recognized in the subsurface. Carbonate sediment generated on the Mississippian Burlington shelf moved southward by gravity flows from the shelf margin to positions on a prograding ramp in Arkansas where overlapping deposits with lobate geometries accumulated. These deposits are recognized in outcrops of the Boone Formation. Stratigraphic units within the Boone are also identified as the Mississippian lime and Reeds Spring Formation, and are targets for hydrocarbon exploration in Oklahoma.

The Hindsville Quarry located in the northeastern portion of Washington County, Arkansas, operated by APAC Central, has exposed walls each in excess of 1000 feet in length and wall heights near 114 feet. Beaver Lake Dam Quarry is located west of Eureka Springs, Arkansas and is operated by U.S. Army Corps of Engineers, and also has exposed quarry walls the reach 75-80 feet in height. The walls at both sites were photographed with the purpose of creating panoramic views of each of the walls. Stratigraphic boundaries within each wall were positioned to define lobe packages and internal facies. Selected intervals were then made into thin section samples for a petrographic study. A distinct coarsening up pattern in the grains was recorded. The use of Terrestrial LiDar scans that were captured four years ago were used to determine stratigraphic pattern, bedding planes and orientation of inaccessible quarry walls of the study areas. Terrestrial LiDar allows improvements of current field methods by quantifying observations and visually capturing information visible and invisible to the human eye (Bellian, et al, 2005). Productive intervals within the Mississippian carbonates of north-central Oklahoma have not been

positioned with respect to depositional or diagenetic facies. The methods used in this study provide criteria by which lobe boundaries can be recognized in the subsurface. The petrography indicates where within the lobe porous and permeable units exist. Terrestrial LiDar scans allowed for the designation of the quarry wall's chert content and access to areas that were inaccessible.

Acknowledgements

I would like to thank those who have donated their time and effort in the completion of this thesis. Dr. Doy Zachry, thesis director, for his contributions as an instructor and advisor, as well as his support and excellent editing of the thesis. Dr. Christopher Liner, of the University of Arkansas, for his involvement in the preparation of posters and presentations for professional meetings, and Dr. Ralph K. Davis, of the University of Arkansas, who provided advice, encouragement and a part time work study during my career here at the University of Arkansas.

A special thanks goes to Will Cains, who provided the camera for photographs of the rock facies at Hindsville Quarry.

I owe a great deal of gratitude to APAC Central for allowing access to the Hindsville Quarry and assistants in walk throughs while visiting. Without their support, this project would have never gotten off the ground.

I also want to thank Jackson Cothren and Malcolm Williamson from The Center for Advanced Spatial Technologies (CAST) at the University of Arkansas for supplying the Terrestrial LiDar Scans and photos of the Beaver Lake Dam Quarry. They were also kind enough to supply a workstation in their office so I can view, edit and manipulate the scans to suit my needs for my thesis. They were truly valuable in learning how to use the software that's required to view the scans and I couldn't have done it without them.

Last, but not least, I express the deepest appreciation to all the great friendships I have made here at the University of Arkansas. This department is truly a wonderful thing and I am so honored to have been able to be a part of the Geoscience family.

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Figures

Introduction

The Lower Mississippian section is very productive in the southern midcontinent, but the reservoir characteristics are not well known. With the encouragement from the University of Arkansas Geosciences Department, access to the Hindsville Quarry (Figure 1) that's operated by APAC Central and Beaver Lake Dam Quarry (Figure 2) that's operated by U.S. Army Corps of Engineers, this study was carried out to isolate and describe a single lobe, or multiple lobes, from three-dimensional exposures in quarry walls at both sites that are slightly over thirty nine miles apart from one another (Figure 3), to provide criteria by which lobes can be recognized in the subsurface. Since terrigenous clastics and siliceous sediments are found at both sites the argument of how the lobes occurred is that as the Mississippian Burlington shelf moved southward by gravity flows from the shelf margin to positions on a prograding ramp in Arkansas, the gravity flows produced pulses of carbonate sediment that formed the lobes seen in the subsurface at both quarries. The use of Terrestrial LiDar scans that were shot in 2011 were used as a geologic component to determine stratigraphic pattern, bedding planes, orientation and chert content of the inaccessible quarry walls of this study. Lower Mississippian carbonates in the subsurface of northeast Oklahoma and northwest Arkansas represent a single depositional sequence bounded by type 1 erosional unconformities (Manger and Shelby, 2000). This single transgressive sequence contains the St. Joe Limestone at the base of the sequence overlain by the Boone Formation. The Lower Mississippian carbonates crop out in parts of northwestern Arkansas, southwestern Missouri and northeastern Oklahoma. Lower Mississippian strata, Kinderhookian to Osagean in age (Figure 4), are underestimated from a reservoir standpoint in the subsurface of northeast Oklahoma, mainly due to the shortage of recent work in the region.

Figure 1: Hindsville Quarry located at 19953 Highway 303 Hindsville, AR 72738 Operated by APAC-CENTRAL. (Hindsville, AR. Map. Google Maps. Google, Jan 2014. Web. Jan 2014).

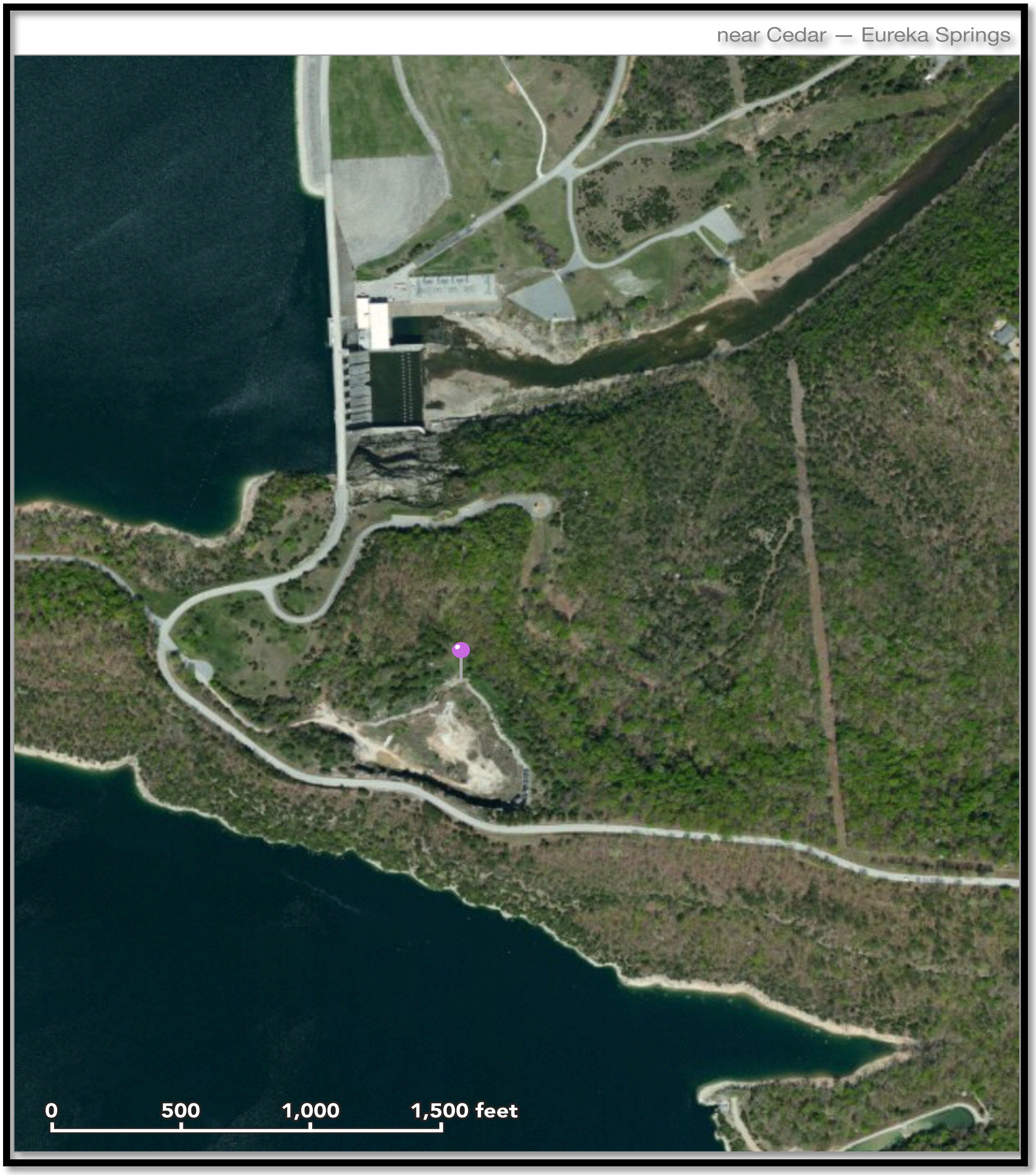

Figure 2: Beaver Lake Quarry (purple pin) is located west of Eureka Springs, Arkansas and is operated by US Army Corps of Engineers. (Eureka Springs, AR. Map. Google Maps. Google, Jan 2014. Web. Jan 2014).

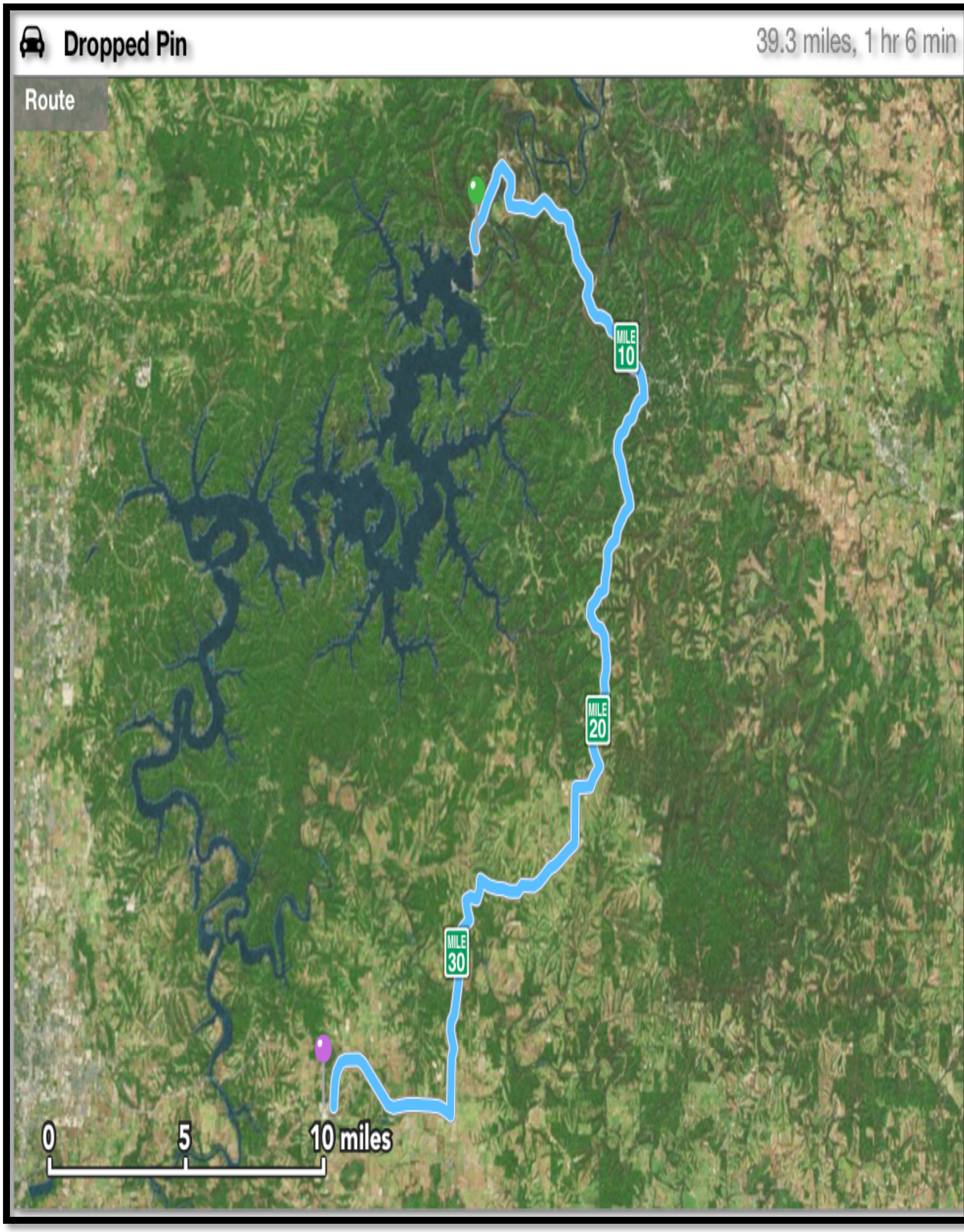

Figure 3: Satellite image of the locations of Beaver Lake Dam Quarry (green pin) and Hindsville Quarry (purple pin), which are 39.3 miles apart. (Eureka Springs, AR. Map. Google Maps. Google, Jan 2014. Web. Jan 2014).

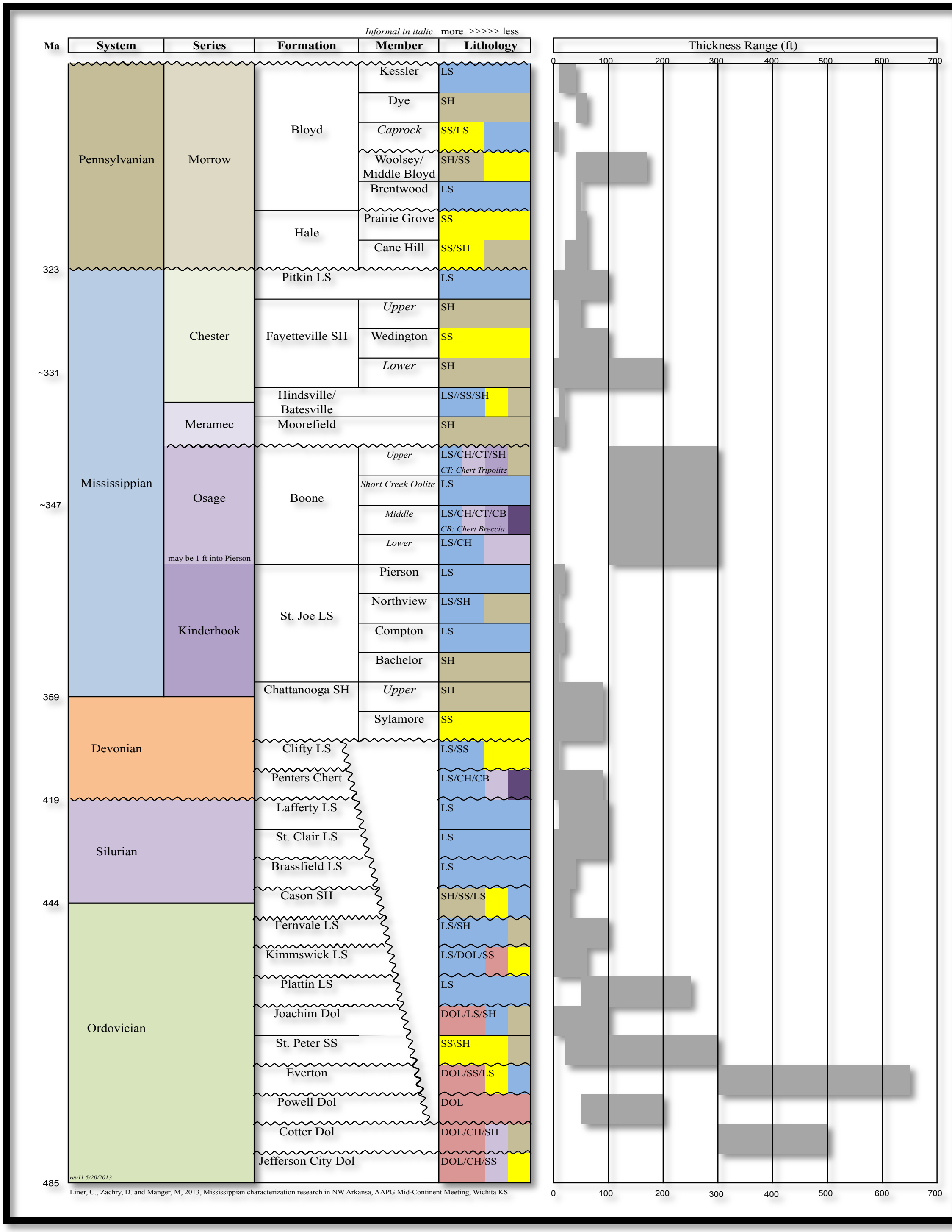

Figure 4: Stratigraphic Column of formations and members found in Northwest Arkansas. (Liner, C. L., Zachry, D., and Manger, W. L., 2013).

Depositional Environment

The Reeds Spring Formation is situated within the lower part of the Boone Formation and is composed of thin beds of alternating fine-grained limestone and dark gray to blue gray and tan chert (McFarland, 1998). The chert in the upper portion is considered late diagenetic chert associated with grain-supported lithologies, whereas the chert in the lower portion of the Reeds Spring Formation is considered penecontemporaneous chert and is associated with mud supported lithologies (Liner, 1980). The inferred depositional environment of the Reeds Spring Formation is that of a sloping ramp of moderate water depth during maximum sea-level highstand in Osagean time (Mazzullo et. al., 2010). The presence of chert in the formation is not considered to be synonymous with a specific depositional environment because it is present in Mississippian rocks in shallow- to deeper-water deposits. As the formation pinches out depositionally to the south-southwest (e.g., Laudon, 1939 and Huffman, 1958) it must also have deepened in this direction, although deep-water facies are not exposed in the outcrop area (Figure 5). Reeds Spring is composed of non-porous lime mudstone and chert, but the limestone's are organic rich and are highly fluorescent with the occurrence of oil (Mazzullo et. al., 2011). The lime mudstones of this formation are thought to pass up-dip into the Burlington-Keokuk Formation, which at the time was the "carbonate factory", which supplied lime mudstones to the slope environment (Mazzullo et. al., 2010).

The Reeds Spring Formation lies stratigraphically between a section of upper Kinderhookian to lower Osagean limestones, siltstones, and shales and upper Osagean limestones, all of which are crinoid-rich and which are inferred to have been deposited in various low to high energy, shallow-marine ramp environments on the southwestern and western flanks of the Ozark Dome

(Boardman et al., 2010; Mazzullo et al., 2010). Based on lithology the Reeds Spring contrasts with these units because it is a dominantly dark lime mudstone and locally light colored. This suggests' a depositional environment in a uniform low-energy setting. Considering that the formation is not composed of pelagic skeletal grains such as those that comprise chalks or other deep-sea carbonates, a section of lime mudstone as thick as the Reeds Spring must have derived its sediment from an up-dip shallow-water carbonate shelf where sediment production and off-bank sediment transport were high (Mazzullo et. al., 2011). The Reeds Spring Formation most often overlies the Pierson Member of early Osagean Age. In the subsurface the Reeds Spring Formation unconformably lies on top of the Devonian Chattanooga Shale. Chert is a major component of this formation (Mazzullo et. al. 2011; Liner 1980).

Gutschick and Sandberg (1983) formed a depositional model for a carbonate ramp setting that can provide some further insight into proposed down-ramp movement of carbonate sediment during the maximum flooding interval in the Lower Boone Formation. By setting the dip angle to 5 feet (the maximum slope angle suggested by Gutschick and Sandberg (1983)) for the ramp model (Figure 5), the water depth would reach the St. Joe Formation. A water depth that surpasses 200 feet leaves the oxygen minimum (OM) zone and is approaching the lower limit of sufficient light penetration to support photosynthesis, and it would lie below both effective (clear weather) and storm wave base. Thus, both green algae that produce carbonate mud and many invertebrate groups that fed or grew on those algae, as well as associated benthonic forms, would not inhabit such an environment, and would not support a robust carbonate factory (Manger, 1988). The depositional setting would more probably receive terrigenous clastics, and siliceous sediments, which is found at both sites and therefore the argument that pulses of submarine downslope flow occurred along the ramp by gravity flows, in a depositional environment of deep water is supported.

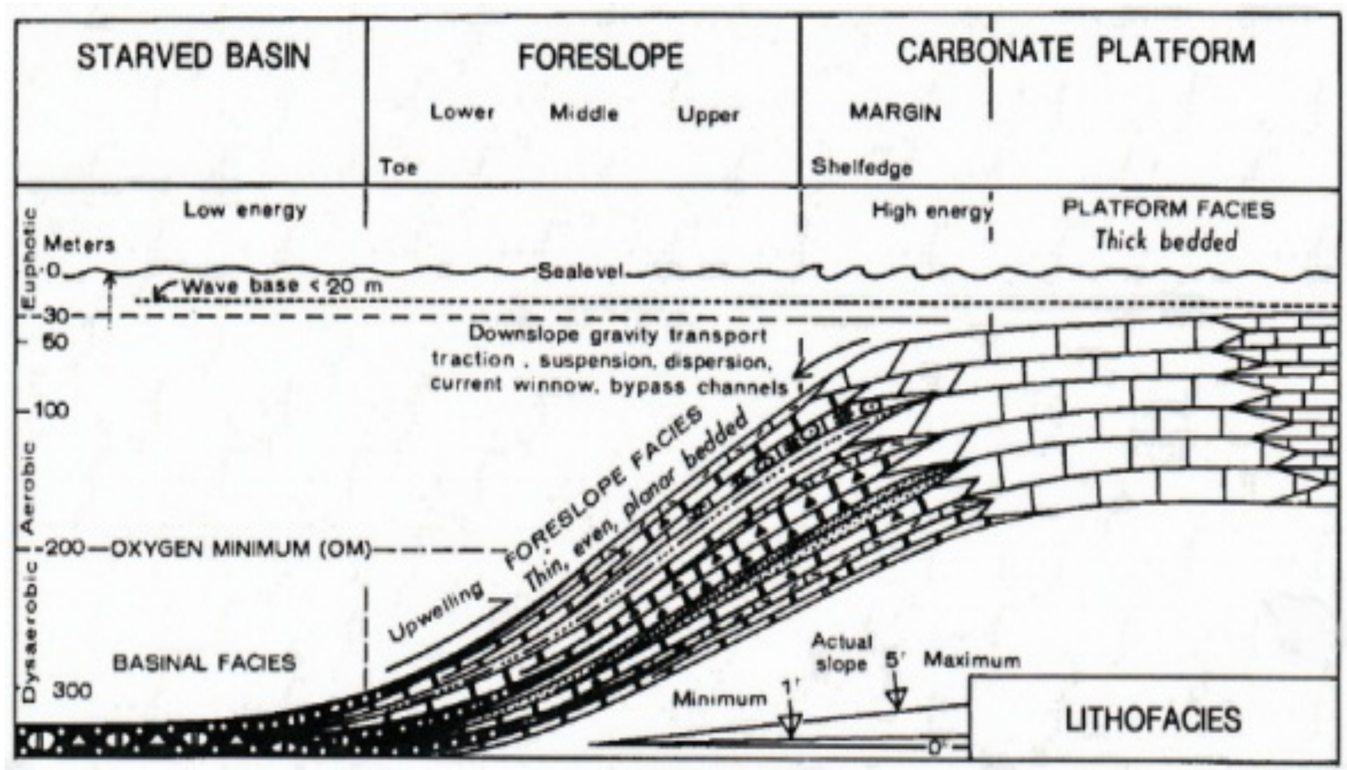

Figure 5: Generalized diagram of Platform Margin-Foreslope-Starved Basin Relationships. (Gutschick, R. C. and C. A. Sandberg. 1983).

Methods

Stratigraphic Interpretation

The Hindsville Quarry located in the northeastern portion of Washington County, of northwest Arkansas and operated by APAC- Central, has exposed walls each in excess of 1000 feet in length and wall heights as high as 114 feet. Beaver Lake Dam Quarry is located west of Eureka Springs, Arkansas and is operated by U.S. Army Corps of Engineers, and also has exposed quarry walls that reach 75-80 feet in height. The walls were photographed with the purpose of creating panoramic views of each of the walls. Stratigraphic boundaries within each wall were positioned to define the stratigraphic zone(s) where the lobes occur. Once this was completed the photos were used to make correlations between the lithologies found at both quarries and the stratigraphic column of Reeds Spring Formations' (lower Boone Formation) lithologies. The camera used to photograph the quarries was a Canon EOS Rebel T3i 18 MP CMOS Digital SLR Camera and DIGIC 4 Imaging with EF-S 18-55mm f/3.5-5.6 IS Lens.

Petrographic Interpretation

Selected intervals were prepared for thin sections and sampled for the petrographic study. The type of chert present in each section was also recorded to determine if it's diagenetic chert or penecontemporaneous chert. The thin sections were viewed using the Leica DM750 LED Biological Microscope with ICC50HD Camera Module - 3 Mega Pixel. The camera modules allowed for pictures of the thin sections and were saved as a JPEG file. The lens objective was set at 2.5X.

Terrestrial LiDar/ Cyclone

The Center for Advanced Spatial Technology (CAST) at the University of Arkansas, Fayetteville provided the scans from the Terrestrial LiDar scanner. All terrestrial laser scanning (TLS) works by a laser pulse that leaves the instrument in a calculated direction, travels to the remote target, bounces off the target and returns to the instrument (Bellian, et al, 2005). The return time of the laser pulse allows the calculation of the distance. These distances are then converted from a spherical to a Cartesian coordinate system as a point in space that lies on the scanned surface. The range measurements and orientation are collected in a data set called a point cloud. A mesh formed from the aligned points serves as a basis for the digital outcrop model (DOM). By using the Terrestrial LiDar it creates a dense point cloud because it's a remote sensing tool. The use of Cyclone allowed for the identification of lithology and stratigraphic pattern of the quarry walls. The intensity values are used to help register multiple scans and discriminate between different lithologies. The color intensity map uses different shades of orange, which represent the geologic features that differ to decipher the key lithologies, specifically chert and limestone. This equipment was used in 2009 by Terryl G. Daniels Jr. and were used in this thesis as a geologic component for correlation between stratigraphic interpretation in the field and stratigraphic interpretation using the LiDar scanner. The scans served as a reaffirmation of the stratigraphic interpretation of the quarry walls at both sites since all photos in the field were shot from 40 feet away from the wall as a safety precaution.

Results

Stratigraphic Interpretation

Two sites in Northwest Arkansas were visited for interpreting the lithology of the Reeds Spring Formation that represents the lower Boone Formation: Hindsville Quarry and exposures at the Beaver Lake Dam Quarry. The lithology of the Reeds Spring Formation is for the most part consistent in outcrops. At both sites visited the outcrops were interpreted as being dominantly dark grey limestone and chert. Also seen in plan view with a hand lens, the limestones are non-porous mudstones with some crinoids and brachiopods along with rare rugose corals and bryozoans (which will be further discussed in petrographic results). A smell of oil is generated when the rock is struck with a hammer.

At Hindsville Quarry on the east side of Arkansas Highway 303, the chert is dark gray to black, and occurs as laterally continuous to discontinuous beds, with layers of nodules that are a few inches to a few feet thick. The discontinuous layers of anastomosing chert nodules is noticeable at Hindsville Quarry and is interpreted as having a multi-generational origin, which is a characteristic attribute of the Reeds Spring and/or Lower Boone Formation in surface exposures. Such cherts have dark gray to black interiors and lighter gray rinds, and their presence and association with medium to dark gray lime mudstone is a key to recognizing the formation in the subsurface (Mazzullo et. al., 2011). The lobate feature is seen along the eastern side of the quarry (Figure 6) with the lobes distal end thinning towards the southwest. The lobe is also located in the lower section of the Reeds Spring Formation, with mud-supported texture. The grain texture of the rocks that make-up the quarry walls at Hindsville Quarry showed evidence for mud-supported texture at the base to grain-supported at the top, so there’s a coarsening up sequence in rock texture. The quarry wall that contains the lobes is dominantly mud-supported in grain texture though.

At Beaver Lake Dam, just west of Eureka Springs, Arkansas (Section 10 T20N-R27W), there are several exposures along Arkansas 187 after crossing Beaver Dam. This includes natural exposure in the valley of the White River of Lower Ordovician and Middle Devonian strata below the overlook, continuation of the White River valley behind the overlook that is accessible by a wooden staircase, and a quarry developed by the U.S. Army Corps of Engineers to provide product to maintain the dam site. Beaver Lake Dam Quarry was the second site visited for this study. Of particular interest, is the suggestion of down-ramp truncation surfaces produced by lobate movement within the lower Boone (Figure 7), since it also occurs in the same stratigraphic zone as the lobate features found at Hindsville Quarry. The rock textures that make-up the quarry walls coarsen up from mud-supported to grain-supported and the lobate feature is also found in rocks that contain a mud-supported texture. The belief is that the carbonates formed on the Burlington Platform and were transported down-ramp by gravity-flows. At the top of Beaver Lake Dam Quarry the walls are medium bedded, light gray to light yellowish-brown with dolomite found at the top, where it's yellowish-brown (Figure 8) and off-white chert nodules with some crinoids (Figure 9). Towards the end of Beaver Lake Dam Quarry the wall contains a thin band of dolomite at the top (yellowish-brown) with a single layer of chert in between the dolomite (Figure 10). After the second band of dolomite in the same wall there's a continuous layer of medium bedded chert. It's worth noting that the presence of dolomite isn't found anywhere at Hindsville Quarry and only occurs at the top of the Beaver Lake Dam Quarry. These quarry faces provide significant insight into proposed down-ramp movement of carbonate sediment during the maximum flooding interval in the Lower Boone Formation.

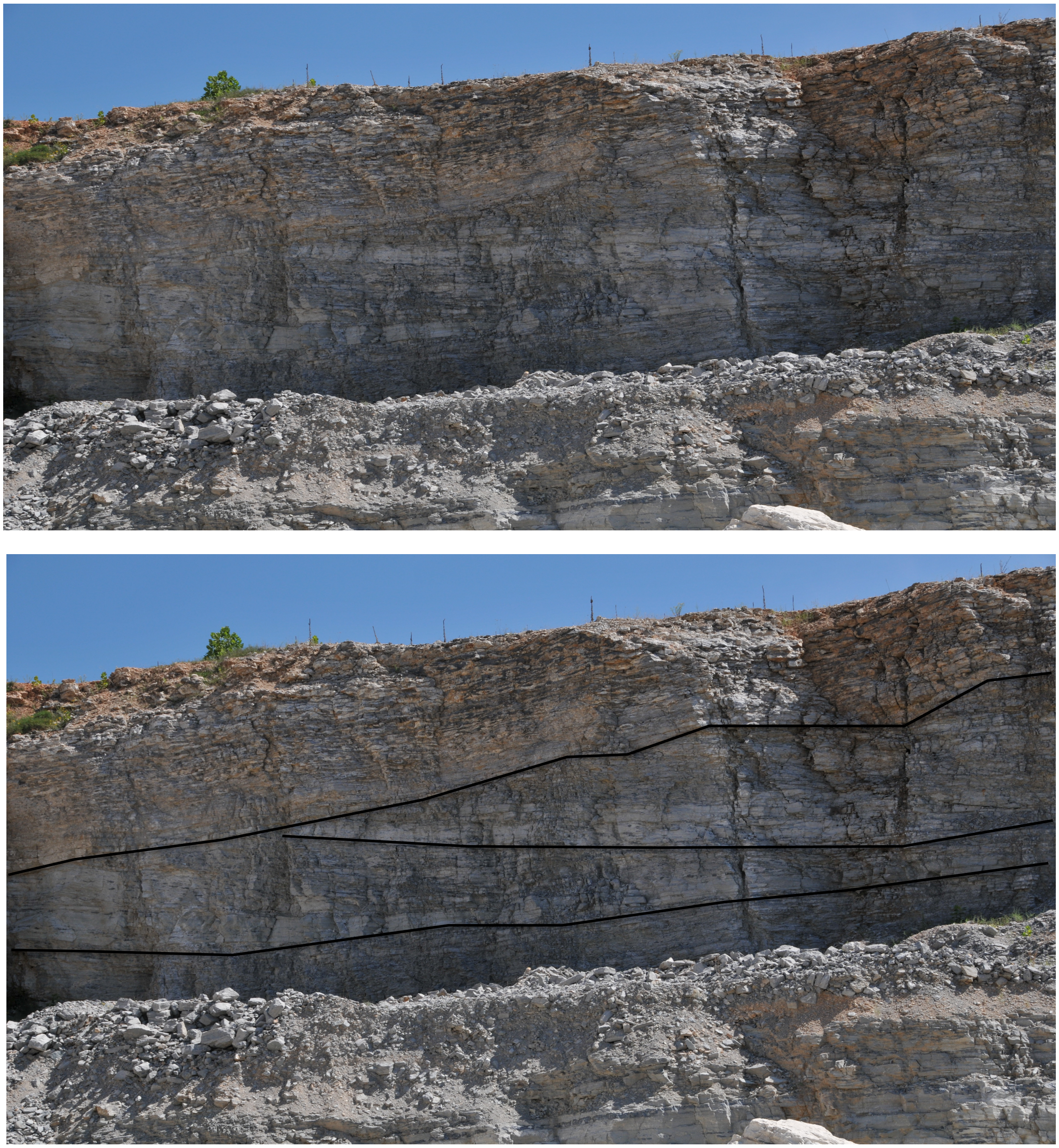

Figure 6: Hindsville Quarry wall face with the sedimentary structure of the wall suggesting a lobate deposition with the occurrence of flow to the southeast. Comparison of outlined lobes to normal view lobes. Unaltered geometric lobes above and outlined geometric lobes below. (Marchese, Elizabeth. Hindsville Quarry. 2013. JPEG)

Figure 7: Erosionally truncated, east-west-trending lobe (arrow) at the quarry near the Beaver Lake Dam just west of Eureka Springs, Benton County, Arkansas. View to the east. Truncated, northward dipping beds along with slight erosional relief, and towards the right side of the photo the beds dip toward the south. These features are evidence of pulses of submarine downslope flow in a deep-water environment that occurred during the formation of the Reeds Spring and/or Boone Formation. (Mazzullo, S., Boardman, D.R., and Wilhite, B., 2011).

Figure 8: Part of the Beaver Lake Dam Quarry Wall that shows the very top of the Reeds Spring Formation. It's medium bedded, light gray to light yellowish-brown. Dolomite found at the top, where it's yellowish-brown. (Marchese, Elizabeth. Beaver Lake Dam Quarry. 2013. JPEG).

Figure 9: Beaver Lake Dam Quarry wall contains limestone, with rare yellowish-brown and off-white chert nodules with some crinoids. (Marchese, Elizabeth. Beaver Lake Dam Quarry. 2013. JPEG).

Figure 10: Beaver Lake Dam Quarry wall contains thin band of dolomite at the top (yellowish-brown) with a single layer of chert in between the dolomite. After the second band of dolomite there's a continuous layer of medium bedded chert. (Marchese, Elizabeth. Beaver Lake Dam Quarry. 2013. JPEG).

Petrographic Interpretation

The Hindsville Quarry and Beaver Lake Quarry from a stratigraphic viewpoint consists of dominantly medium to dark grey limestone and chert. After the stratigraphic interpretation was made thin sections (Figure's 11A- 11H) from both sites were analyzed to gain supporting evidence that both quarries contain rocks with a coarsening up sequence in grain texture and if the lobes are found in the stratigraphic zone of mud-supported lithology.

Petrographic evidence indicates that the limestones are non-porous mudstones with some crinoids and brachiopods, along with bryozoans and rugose corals. There is an abundance of chert in the thin sections as it makes up a large portion of the formation. The chert is mainly dark grey to black and occurs in laterally continuous to discontinuous beds and also as layers of nodules from the middle to base of the formation. It's tannish and/or yellowish grey in color toward the top of the Reeds Spring Formation. Dolomite is present in the thin sections from the Beaver Lake Dam Quarry only (Figure 11B). The dolomite is medium crystalline and occurs only in the thin section taken from the top of Beaver Lake Dam Quarry (Figure 11C). The thin sections that were viewed for interpretation are listed below in detail to gain insight on how Reeds Spring Formation was deposited (Figure 12) and formed the lobes seen in exposures.

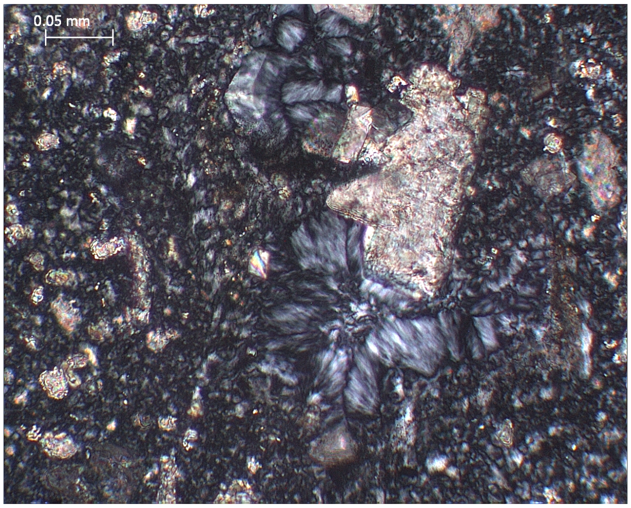

Figure 11 A: 412-1-d1(Cross-Polars) Near 412 at Beaver Lake. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Predominately chert (black) interbedded with calcite (white-to-tan) and microcrystalline quartz (tiny white specks).

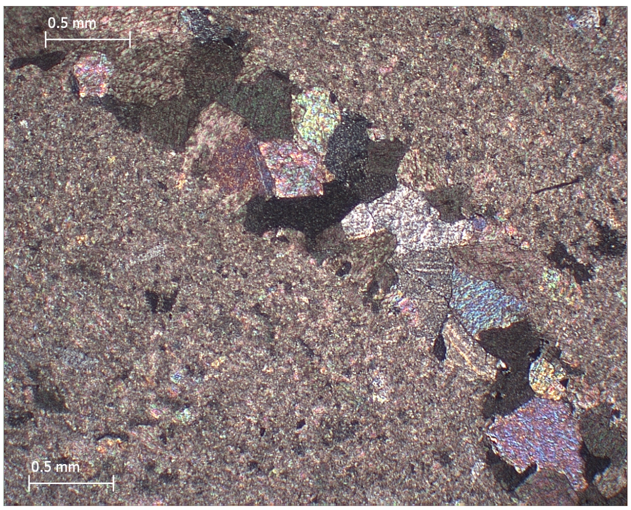

Figure 11 B: 412-1-d2 (Cross Polars). (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Fracture where calcite crystals grow within it. Dolomite surrounds the fracture.

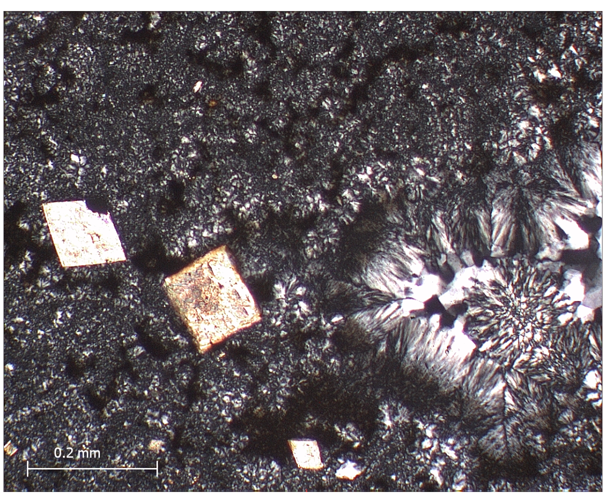

Figure 11 C: 412-B2-d2 (Cross Polars) Near 412 at Beaver Lake. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Predominately chert (black in color) with white colored, rhombic shaped dolomite crystals. Microcrystalline quartz exists within the chert (tiny white specks) and calcite (white) is to the lower right of the image.

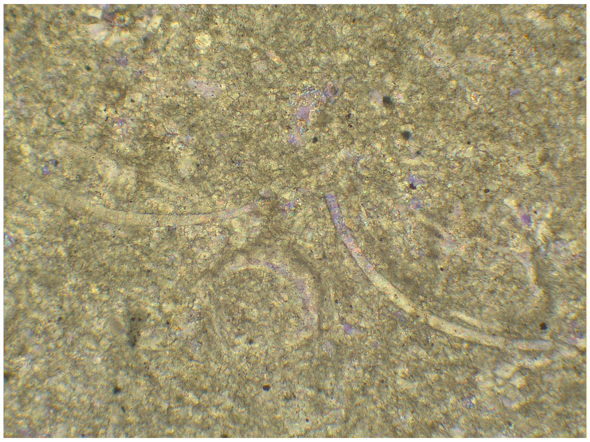

Figure 11 D: HQ-3 (Plain Polarized Light) at Hindsville Quarry. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Burrows within the chert and remnants of brachiopods and bivalves.

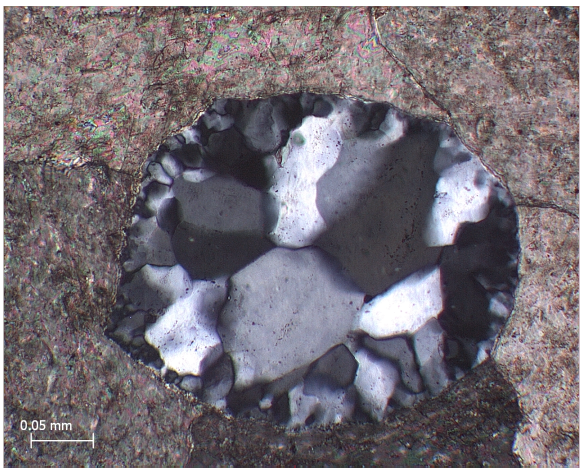

Figure 11 E: HQ-4-1d (Cross Polar) Hindsville Quarry. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Mega-quartz with coarse crystals. Calcite surrounds the mega-quartz.

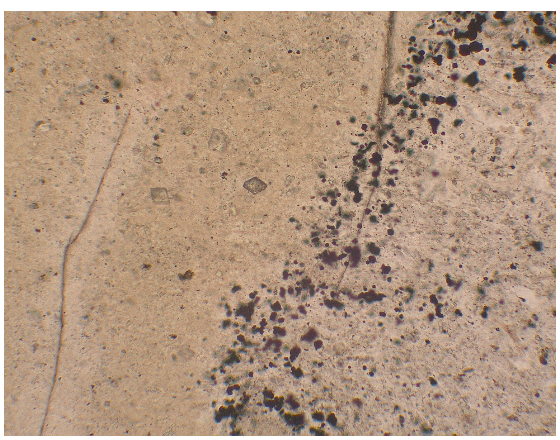

Figure 11 F: HQ-4-Pyrite (Plain Polarized Light) Hindsville Quarry. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Rhombic specks of pyrite, red in color. Opaque.

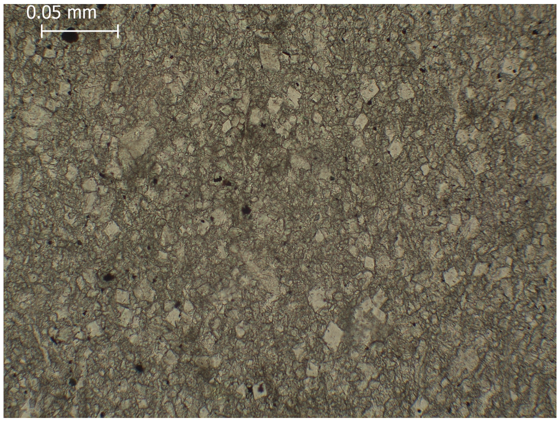

Figure 11 G: HQ-9 (Plain Polarized Light) Hindsville Quarry. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Chert, tannish brown in color, with microcrystalline quartz, light tan-to-white in color.

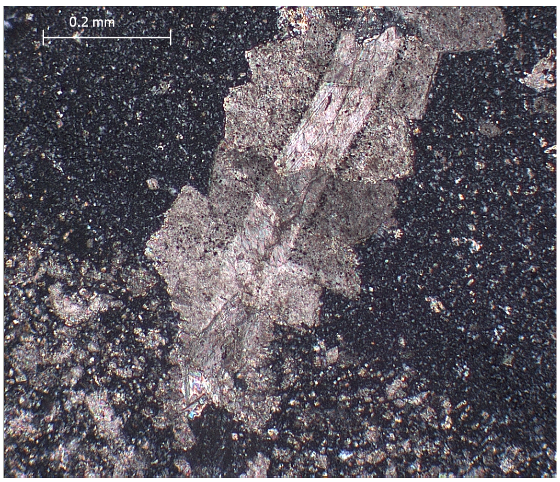

Figure 11 H: HQ-9-d1 (Cross Polars) Hindsville Quarry. (Marchese, Elizabeth. Thin Sections. 2013. JPEG).

Conodont fragment that's surrounded by calcite (greyish-white color). The conodont fragment goes into extinction. Chert (black in color) surrounds the calcite, with some additional calcite dispersed to the bottom of the thin section.

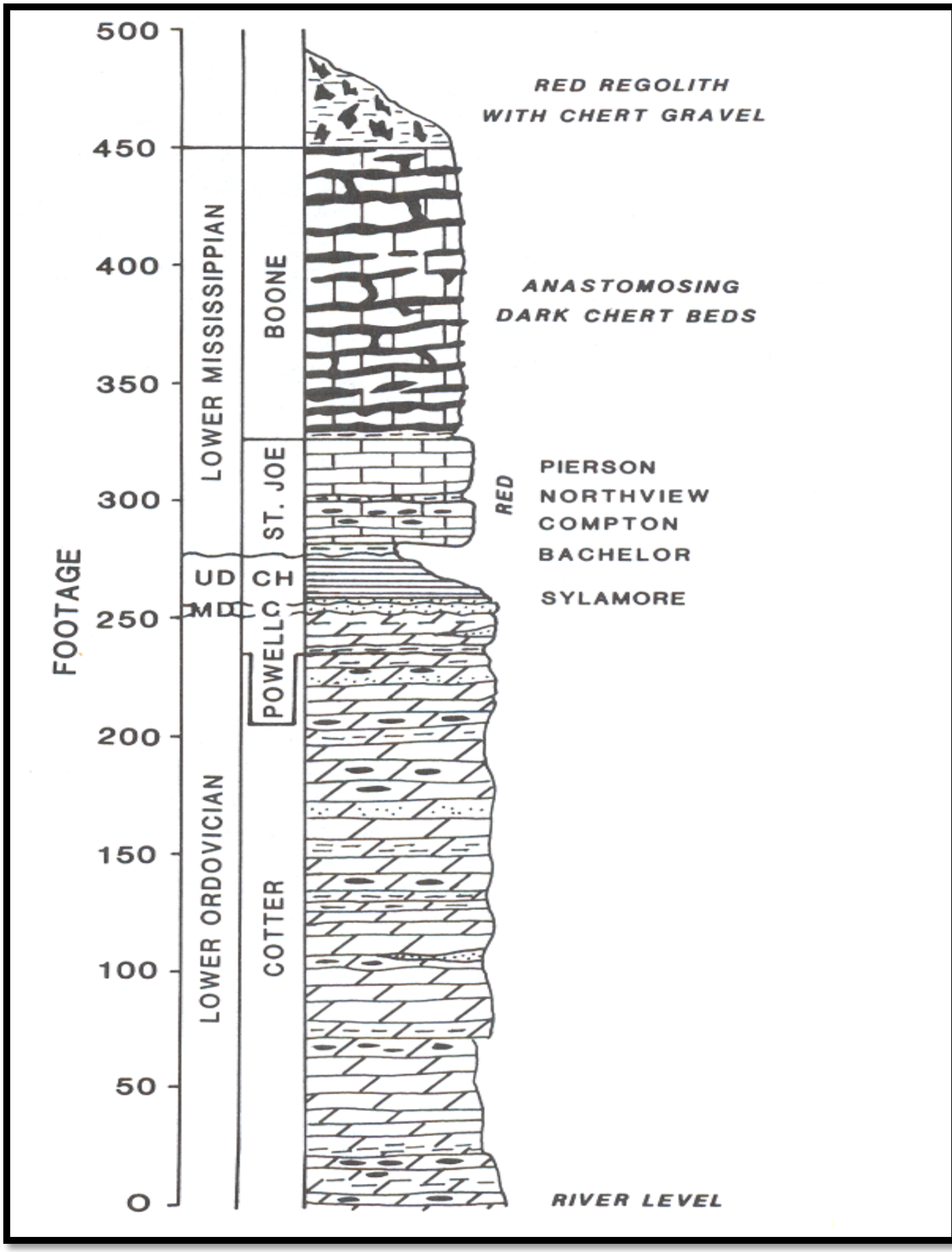

Figure 12: Stratigraphic column showing the lithology of the Hindsville Quarry and Beaver Lake Dam Quarry. (Manger, Walter L.1988).

Terrestrial LiDar Scans

The scans from Hindsville Quarry and Beaver Lake Quarry allowed for more detail in identifying the stratigraphic pattern, bedding and lithology of the quarry's walls. All photos from the stratigraphic interpretation were taken from 40 feet back from the wall, because both quarries are considered active, therefore it's too dangerous to be any closer than 40 feet to the walls. The scans show more detail of the quarry wall faces and were therefore used to support the photos taken with the Canon EOS Rebel camera for the stratigraphic interpretation. The types of scans that were used for interpretation are the photo texture overlay map with intensity values (Figure 13) and the color intensity map (Figure 14). The photo texture overlay map with intensity values are referred to as orthophotos because they use the image from the scanner and apply the photos that were taken from a camera that is attached to the scanner. Cyclone software takes the scan of the quarry wall of interest and matches it to the photo taken at the same place and time. The orthophoto allows for the user to see the stratigraphic patterns, bedding and lithology of the quarry wall. The color intensity map allows for a general view of the chert and limestone content in the quarry walls, which the chert appears as a bright red color and limestone as a bright orange color on the intensity map.

The scans show a coarsening up pattern in grain texture that was identified in the petrographic and stratigraphic analysis. Limestone makes up a large percentage of both Beaver Lake Quarry and Hindsville Quarry. The chert at both localities is dark gray to black, and occurs as laterally continuous to discontinuous beds, with layers of nodules that are a few inches to a few feet thick. The discontinuous layers of anastomosing chert nodules are noticeable at both localities and are interpreted as having a multi-generational origin, which is a characteristic attribute of the Reeds

Spring and/or Lower Boone Formation in surface exposures. Therefore, the scans that produced the orthophotos and color intensity map to distinguish the chert and limestone are used to support the stratigraphic interpretation.

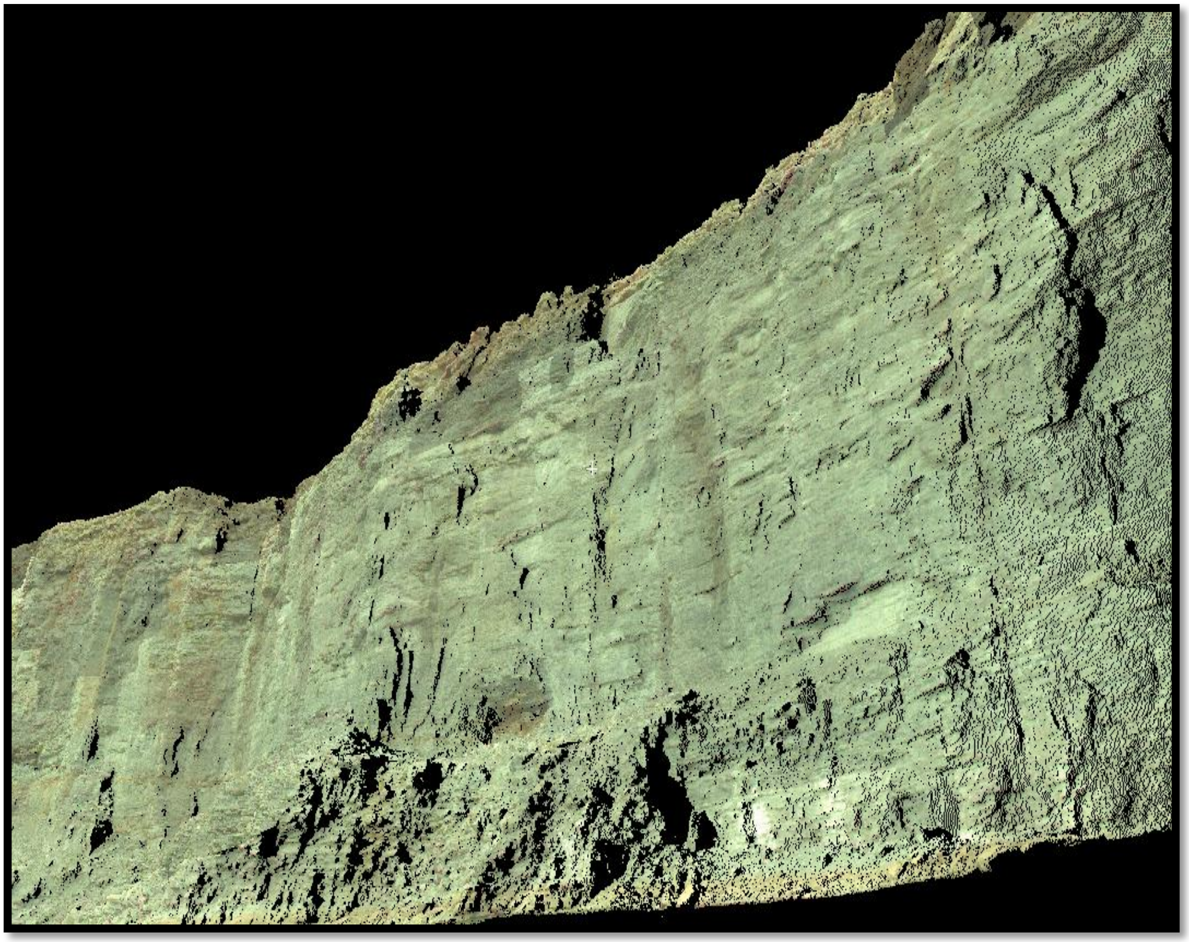

Figure 13: Terrestrial LiDar scan with photo texture overlay. This scan is from Hindsville Quarry and depicts a single wall face that's predominantly limestone with some interbedded chert. (Marchese, Elizabeth. Terrestrial LiDar scan. 2014. JPEG).

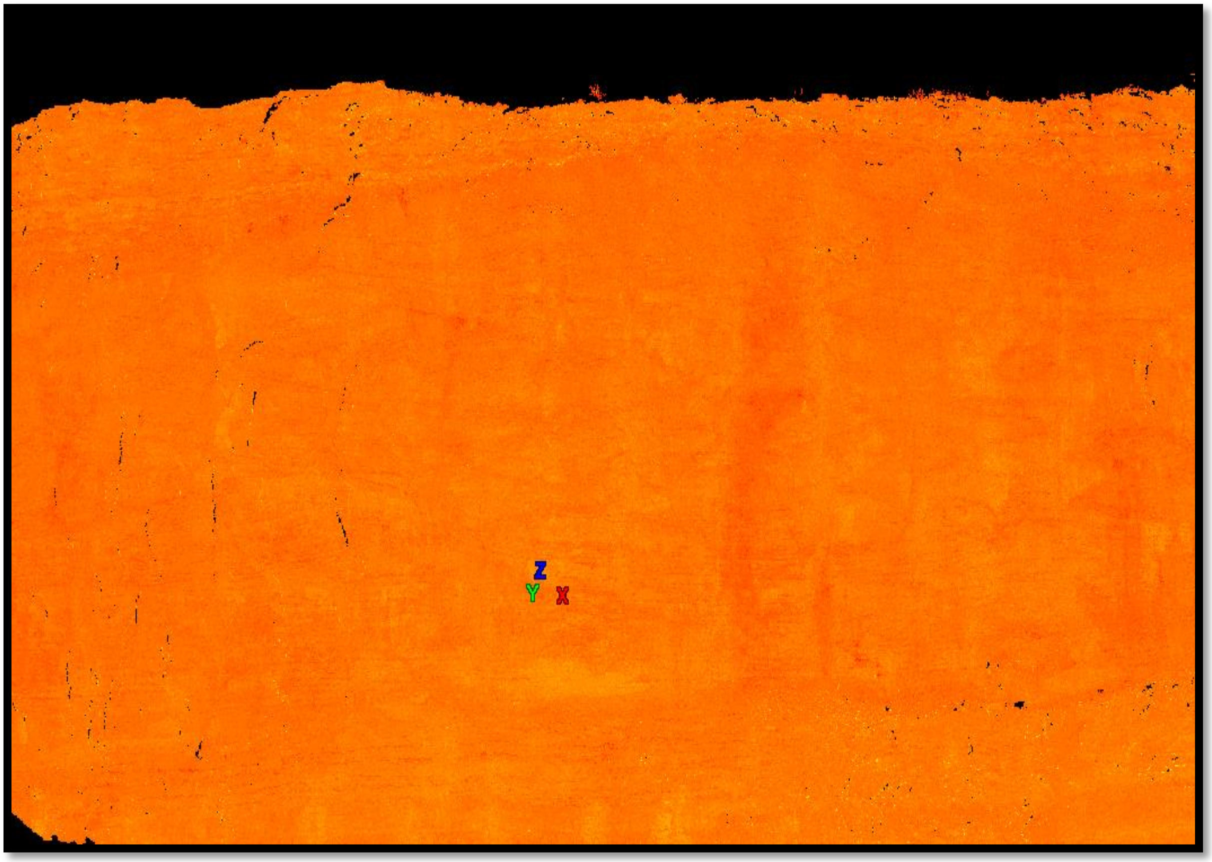

Figure 14: Color Intensity Map using Terrestrial LiDar. This scan was shot at Hindsville Quarry and the wall face is predominantly limestone (orange color) with some interbedded chert, but is hard to distinguish. (Marchese, Elizabeth. Color Intensity Map. 2014. JPEG)

Discussion

Carbonate sediment accumulated on the Burlington Shelf, which was a large, almost craton-wide shelf that extends north of Arkansas, into Missouri, Iowa and further north (Figure 15). The shelf was bordered by a ramp inclined to the south into southern Missouri and Arkansas. Fine carbonate sediment accumulated on the shelf and at the shelf margin over-toped the margin and descended in an episodic series of gravity flows that descended the ramp and ultimately accumulated as lobes. The sheets of sediment in each flow would be expected to thin laterally, leaving a lobe that terminated laterally and at its distal end. Lobes would originate from different positions along the shelf margin resulting in overlapping lobes and variable transport directions. The outcome that was accomplished was to establish their very existence in the quarry walls, remembering that the sequence stratigraphy in this study has been interpreted as a fairly deep-water environment that underwent submarine downslope gravity flows, which caused erosion and truncation at the crest of the lobes.

Figure 15: Paleogeography of mid-continent U.S. during the middle Mississippian, in the Osagean Series. The shelf was bordered by a ramp inclined to the south into southern Missouri and Arkansas. (Lane and Dekeyser, 1980).

Stratigraphic Interpretation

The quarry faces from both sites provide further insight into proposed down-ramp movement of carbonate sediment during the maximum flooding interval in the Lower Boone Formation. The sedimentary structure of the walls at Hindsville Quarry and Beaver Lake Dam Quarry suggests lobate deposition with the flow direction to the southeast. The stratigraphic pattern shows the continuous pattern of wedge shaped geometries crossing and stacking on top of each other. Throughout the quarries in the same stratigraphic zone the wedge-shaped geometries can be identified, in mud supported rock textures, but the wall its self coarsens up in rock texture. The stratigraphic interpretation suggests a coarsening up texture, from mud-supported to grain-supported rocks in both quarry walls. According to Shanmugam and Moiola (1985) a non-channelized lobe is described as existing in the subsurface of rock units face that has a coarsening up style that was increased by sediment delivery.

At Beaver Lake Dam Quarry there's a low lobe trending in the east-west direction and is erosionally truncated within the outcrop. A similar lobe feature is also present at the Hindsville Quarry, in the same stratigraphic zone of rocks that are mud-supported grain texture. Similar evidence of this lobate feature within the formation, with or without obvious breached folds but locally with thin chert breccias, is present at several other outcrop and quarry exposures in Missouri and Arkansas (Mazzullo et. al., 2011). It's inferred that these all represent multiple, closely stratigraphically spaced lobes, with the chert breccias immediately overlying the lobes, specifically at the Beaver Lake location. The wedge shaped geometries crossing and stacking on top of each other that are seen at Hindsville Quarry and Beaver Lake Dam Quarry are evidence of pulses of submarine downslope flow in a deep-water environment that occurred during the formation of the Reeds Spring and/or lower Boone Formation by gravity flows.

Both quarries show that the Lower Boone exhibits low-angle, cross-bedding through its entire exposure in the same stratigraphic zone. At Hindsville Quarry, the Lower Boone exhibited planar beds, with rhythmic alternations of nodule dark chert and calcisiltites in persistent, planar beds. At Beaver Lake Dam Quarry the inclined planar beds, with low angle truncations are exposed in the lower section of the Boone Formation and/or Reeds Spring. The carbonates that make-up the St. Joe Formation and Boone Formation were generated on the Burlington Platform, and were transported down-ramp in a lobate pattern. Although these are positive areas on the seafloor, one would expect internal structures in these lobes that resemble low-angle, trough cross-stratification, which is present in a section that would be nearly perpendicular to the axis of the lobe. The front of the block diagram illustrating trough cross-stratification (Figure 15) would be the same view as the quarry face, although, the scales would be quite different (Manger, 1988). Looking at the west wall from Hindsville Quarry (Figure 16), the block diagram for a section parallel to the axis of the lobe predicts the view, and the same can be said about Beaver Lake Dam Quarry. The exposure comprises planar, inclined beds with some minor scour (Figure 17).

Lobate movement of sediment in modern carbonate environments from storm activity and gravity flows is common. On the Bahama Platform, there is a change in water depth from less than 100 feet to more than 5000 feet at the shelf-edge (Manger, 1988). At the south end of the Tongue of the Ocean (Figure 18), clean bioclastic sand and oolite produced higher on the Bahama Platform are moved by tides, occasional storms, strong bottom currents and gravity flows toward the shelf edge and off into deep water. At South Cat Cay (Figure 19) clean oolites are moved in spillover lobes, from the shelf edge onto the Bahama platform by episodic and/or pulses of storm activity. Gravity flows produce the same shape and pattern of spillover lobes, but is generated differently. To initiate the process of lifting the sediment from it's initial spot, the sediment needs to become buoyant. For gravity flow to occur there needs to be contrasting densities between two constituents. In this scenario the two constituents are the carbonate sediment and fluid. The gravity flow picks up the buoyant sediment because the sediment's density contrasts the fluids density, and therefore, transports the sediment down the ramp in pulses. The area of lobate transport in the southeastern Tongue of the Ocean occurs over a distance averaging 30 miles, while at South Cat Cay, the distance of spillover is only 1.25 miles. The belief for this study is that similar lobes of sediment from the Burlington Platform were moved down-ramp by gravity flows during the Lower Mississippian. The evidence of the flow direction occurring in the southeast is best seen in these quarry faces and walls at the Beaver Lake Dam Quarry and Hindsville Quarry.

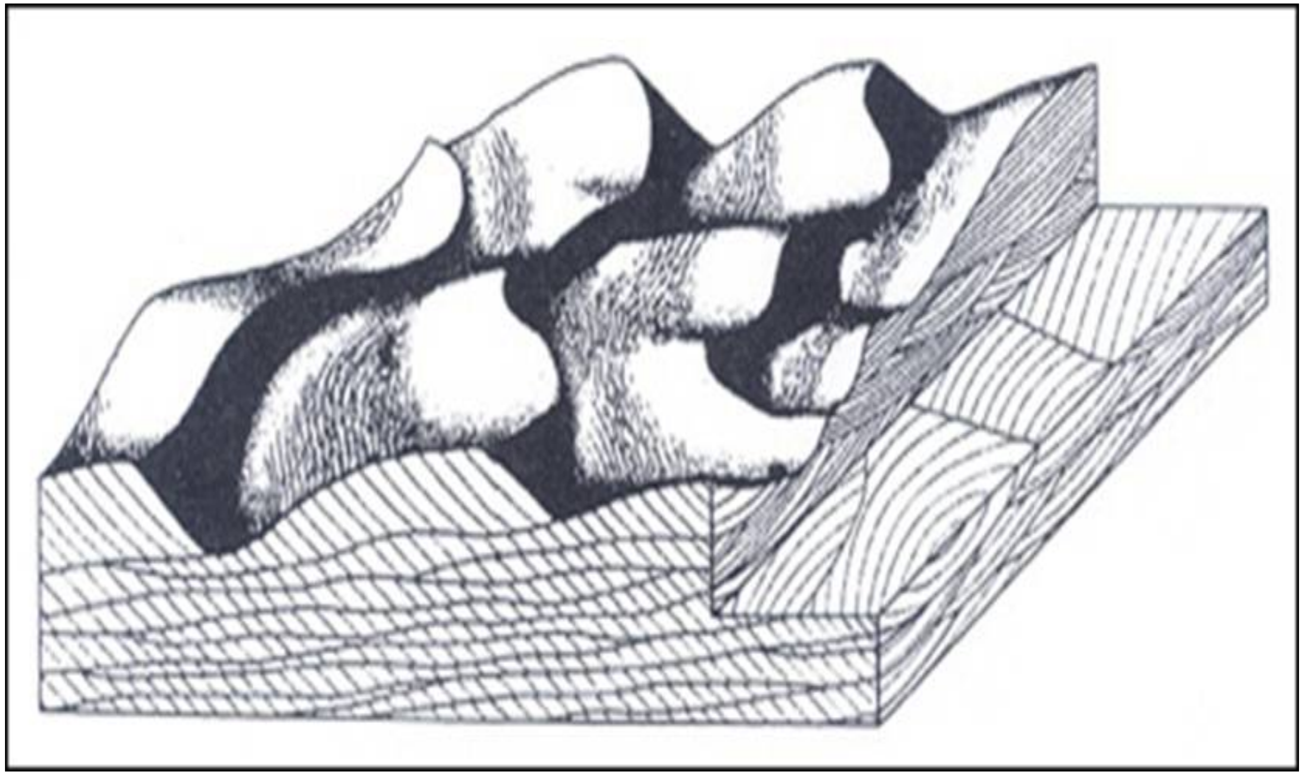

Figure 16: Hindsville Quarry – Block Diagram Showing Trough Cross-bedding with festoon-shaped units. All transitions between planar and trough cross-bedding are known, and scales can vary from centimeters to meters. (Reineck H.E., Singh I.B. 1980).

Figure 17: Hindsville Quarry – Low-angle, trough cross-bedding perpendicular axis of delivery, Lower Boone Formation, Northwest Wall, Hindsville Quarry. (Marchese, Elizabeth. Hindsville Quarry. 2013. JPEG.)

Figure 18: Hindsville Quarry- Inclined Planar Bedding parallel to delivery axis, Lower Boone Formation, West Wall, Hindsville Quarry. (Marchese, Elizabeth. Hindsville Quarry. 2013. JPEG.)

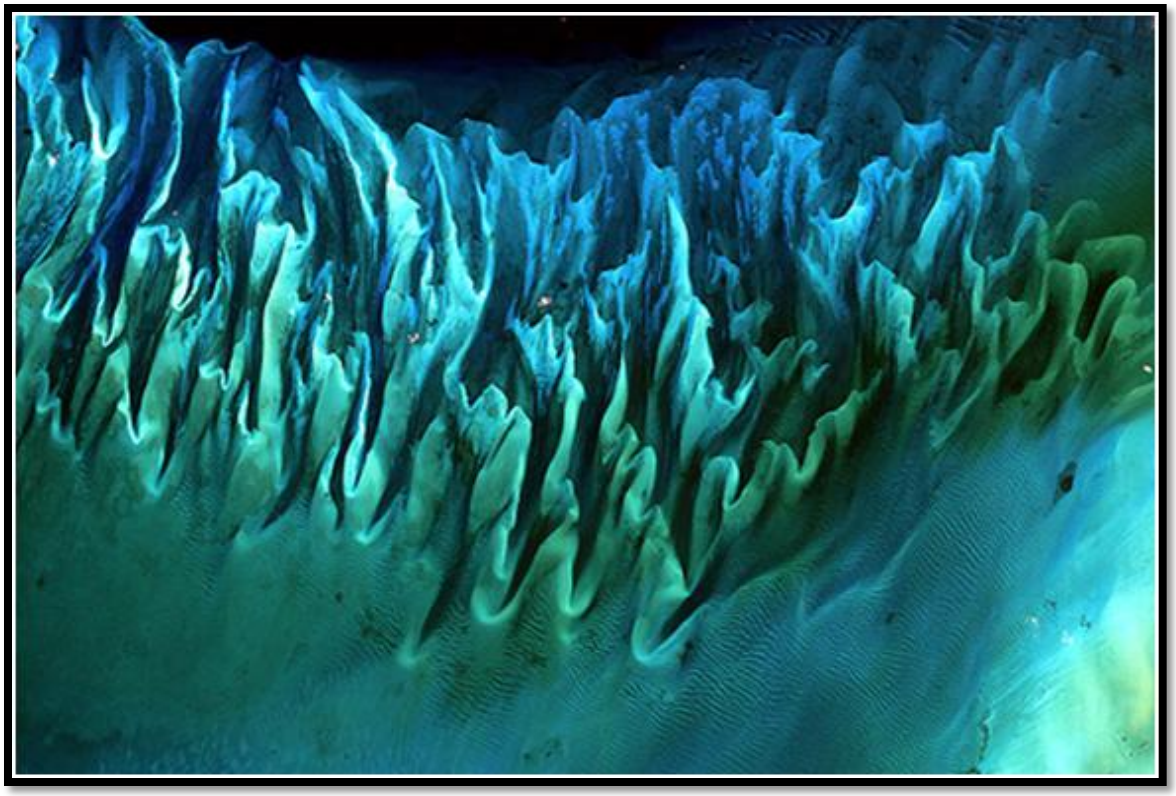

Figure 19: Hindsville Quarry – Lobate Movement of Clean Skeletal Sand and Oolite, Tongue of the Ocean, Bahama Platform. (News & Events - College of Marine Science, University of South Florida. N.p., n.d. Web. 09 Apr. 2014).

Figure 20: Hindsville Quarry – Lobate Movement of Clean Oolite, South Cat Key, west side of the Bahama Platform. (Laverdiere, Jim. Web. 09 Apr. 2014).

Petrographic Interpretation

After analyzing the thin sections from Hindsville Quarry and Beaver Lake Dam Quarry there's no evidence of pelagic skeletal grains that would be found in deep sea carbonates. The argument that the lime mudstones, which make up Reeds Spring Formation and the lower Boone Formation, were transported from a high up-dip shallow water carbonate shelf with submarine downslope gravity flows is supported by the results. Based on conodont evidence (Boardman et al., 2010) the Reeds Spring Formations' moderate depth ramp passed up-dip, to the north, into its coeval facies counterpart – shallow-water, high-energy crinoidal limestones in the lower part of the Burlington-Keokuk Formation (Mazzullo et. al., 2011). Siliceous spicules are present in some of the thin sections that were taken from the base of the formation at Hindsville Quarry. The thin sections taken from the middle of the quarry walls contain small burrows and therefore represent the middle section of the Reeds Spring Formation. Moving up in the formation to the top, the thin sections show that the limestones at both localities become more fossiliferous with crinoid-brachiopod wackestone, and lighter in color. The only difference between the two quarries is the thin bands of dolomite at the very top of the Beaver Lake Dam Quarry.

The presence of dolomite in the thin sections from Beaver Lake Dam Quarry suggests that it's from a larger source of mixed dolostone/limestone found in sedimentary rocks. Dolomite crystals are found in hydrothermal vein deposits or within sedimentary rocks, where they fill their host rock. However, the thin sections from Beaver Lake Dam Quarry show that dolomite surrounds the fracture and calcite exists within the fracture. These dolostone rocks originally formed as limestone marine deposits on ancient shallow seafloors that were later altered to dolostone as magnesium-rich waters moved through them. Therefore, the dolomite is believed to have formed by replacement of some of the calcium in a calcium carbonate limestone deposit with magnesium, while the sediment was undergoing lithification, being converted from layers of dead sea animal shells into crystallized calcite or calcium carbonate. The presence of dolomite also supports the deposition of the Reeds Spring Formations' sediment occurred higher on a slope and/or closer to the source of the transported carbonate.

The thin sections that contain chert are dark grey to black interiors with discontinuous layers of anastomosing chert nodules that have a multi-generational origin. Their narrow fractures are filled with opaque white colored chert. The key to recognizing the chert in the Reeds Spring Formation is that they're associated with medium to dark grey limestones. The anastomosing, multi-generational chert is not seen at either formation that surrounds the Reeds Spring Formation (Burlington- Keokuk on top and Osagean Pierson Formation underneath), so it's a key distinguishing factor. These fractures are interpreted to have formed as a result of early dilatational or load-induced compaction in the shallow-burial, sub-seafloor environment within sediments that were being incipiently silicified (Mazzullo et al., 2009). The characteristic faint burrows present in the limestones within the formation are accentuated and readily visible where the rocks are replaced by chert. Mazzullo and Wilhite (2011) noted that in many places the bases of some chert beds clearly follow relatively large-diameter, branching horizontal crinoid burrows that were also seen in some thin sections. This suggests that silicification was perhaps initially facilitated by pore-fluid movement along burrows that provided pathways of greater permeability relative to non-burrowed beds.

There's essentially no effective matrix porosity-permeability system in the lime mudstones and cherts in the Reeds Spring, even though the limestones locally may have some porosity (mostly micro-intercrystalline pores and micro-vugs). Yet, the limestones and cherts locally produce oil and gas from these rocks, especially in subsurface northern Oklahoma. The thin sections show natural fractures and joints that represent Reeds Spring Formation, so it is inferred that the unit's permeability pathways through these fractures and joints are where the production occurs. Reeds Spring contains hard cherts, which are very brittle and leads to fracturing easily. From an exploration standpoint, areas containing high densities of fractures within this formation are of major importance. Bedding planes and irregular contacts, like the wedge shaped lobes seen in subsurface at both localities, between chert layers/lenses/beds and host lime mudstones, also act as fluid migration pathways in the subsurface. Since there is no effective matrix porosity and permeability system in the lime mudstones and cherts the fluid migration pathway must occur between the irregular contacts, which can be seen in the subsurface by the lobate patterns at both quarries. From a porosity and permeability standpoint, the use of thin sections supports the defense that the multiple packages of sediment formed lobes of chert and lime mudstone, which act as a fluid migration pathway.

Conclusion

Based on stratigraphic interpretation from Hindsville Quarry and Beaver Lake Dam Quarry it has been identified that the continuous pattern of wedge shaped geometries crossing and stacking on top of each other are lobes, and occur in the same stratigraphic zone of mud-supported grain texture. The petrographic study supports the deposition of the Reeds Spring Formations' sediment occurred higher on a slope and/or closer to the source of the transported carbonate, thus creating the cross-bedding and wedge characteristics of the channelized lobes. The presence of dolomite in the thin sections from Beaver Lake Dam Quarry suggests that it's from a larger source of mixed dolostone/limestone found in sedimentary rocks. These dolostone rocks originally formed as limestone marine deposits on ancient shallow seafloors that were later altered to dolostone as magnesium-rich waters moved through them. Therefore, the dolomite is believed to have formed by replacement of some of the calcium in a calcium carbonate limestone deposit with magnesium, while the sediment was undergoing lithification, being converted from layers of dead sea animal shells into crystallized calcite or calcium carbonate.

The stratigraphic and petrographic interpretations support the argument that the truncation and erosion at the crest of the lobes was caused by submarine downslope gravity flows and that the depositional environment is in fairly deep water. Throughout the Hindsville Quarry and Beaver Lake Dam Quarry the wedge-shaped geometries are seen in the lower Boone Formation, in the same stratigraphic zone that's mud-supported in rock texture, so therefore represents a pattern of features suggesting onlapping distal lobes. The flow direction of the lobes found at both quarries is to the southeast and is best displayed in the quarry walls. The use of Cyclone aided as an additional tool for the identification of lithology and stratigraphic pattern of the lobate features and quarry wall faces. The intensity values were used to help register multiple scans and discriminate between different lithologies. The identification of lithology and stratigraphic pattern was shown in Cyclone and enhanced by the orthophoto feature, which allowed for a thorough designation between chert and limestone, while the color intensity map offered a general view of designating limestone from chert. The Lower Mississippian section is very productive in the southern midcontinent, but the reservoir characteristics are not well known. With the encouragement from the University of Arkansas Geosciences Department, access to the Hindsville Quarry that's operated by APAC Central and Beaver Lake Dam Quarry that's operated by U.S. Army Corps of Engineers, this study was successful in isolating and describing multiple lobes from three-dimensional exposures in quarry walls at both sites to provide criteria by which lobes can be recognized in the subsurface.

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